Unveiling the Graviton Mass Bounds through Analysis of 2023 Pulsar Timing Array Datasets

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Strong evidence for the Helling-Downs correlations have been reported by several pulsar timing array collaborations in middle 2023. In this work, we study the state-of-the-art graviton mass bounds by analyzing the observational data of overlap ruduction functions from NANOGrav 15-year data release and CPTA first data release. The data analysis places upper limits on the graviton mass at 95% confidence level, namely, $m_g \lesssim 0.43 \times 10^{-23}$eV for NANOGrav and $m_g \lesssim 0.57 \times 10^{-23}$eV for CPTA. In addition, we discuss implications of these results for scenarios of ultralight tensor dark matter.

I. INTRODUCTION

Based on Einstein's theory of general relativity, the Hellings-Downs (HD) correlation curves have been proposed to characterize a stochastic gravitational-wave background (SGWB) of pulsar timing array (PTA) band [1]. Recently, strong evidence for a stochastic signal that is spatially correlated among multiple pulsars were reported by the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) [2] and Chinese PTA (CPTA) [3] Collaborations, respectively. In particular, the HD correlations were claimed to deserve statistical significance of $\sim 3\sigma - 4\sigma$ by NANOGrav and of 4.6σ by CPTA. The

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European PTA (EPTA) [4] and Parkes PTA (PPTA) [5] Collaborations also claimed that their datasets are compatible with the HD correlations.

However, the overlap reduction functions (ORFs) for a theory of massive gravity could be different from the HD correlations. They depend on the graviton speed and then on the graviton mass, but recovers the HD correlations in the massless limit [6, 7]. The massive gravity was first proposed by Fierz and Pauli in 1939 [8]. It has been extensively studied in the subsequent more than eighty years and the graviton mass has been bounded by a quantity of laboratory and astronomy observations (e.g., see reviews in Ref. [9] and references therein).

During the era of gravitational-wave astronomy, the speed of gravitational waves v_g was shown by the Advanced LIGO, Virgo and KAGRA (LVK) Collaborations to almost coincide with the light speed with a precision $|v_g - 1| \lesssim 10^{-15}$, indicating an upper limit on the graviton mass, i.e., $m_g \lesssim 10^{-22}$ eV [10]. Recently, similar upper bounds were also claimed by other research groups [11, 12], who focused on analysis of the past NANOGrav 12.5-year dataset [13].

In this work, taking into account ORFs for massive gravitons in Ref. [7], we explore the state-of-the-art upper bounds on the graviton mass by analyzing the 2023 NANOGrav and CPTA datasets [2, 3] that supported strong evidence for the HD correlations but did not veto other alternative correlations. The remaining context of the paper is as follows. In Section II, we show ORFs for massive gravitons, with the HD correlations being the massless limit. In Section III, we show a likelihood method for data analysis as well as the resulting bounds on the graviton mass. In Section IV, we show the concluding remarks.

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II. THEORY

In this work, we can consider only the helicity-two modes for simplicity [14]. Conventionally, we may study the massive gravity by analyzing its Lagrangian. However, when we study the propagation only, an equivalent but simple approach seems to concern the dispersion relation, i.e., $\omega^2 = k^2 + m_g^2$, with the graviton speed being defined as $v_g = d\omega/dk$ [10]. Here, m_g is the graviton mass, ω and k stand for the angular frequency and wavenumber, respectively. For subluminal gravitons, we obtain a deviation of the graviton speed from the light speed, i.e.,

$$v_g = \sqrt{1 - \left(\frac{m_g}{\omega}\right)^2} \; . \tag{1}$$

For a typical frequency band, the lower limit on the graviton speed can be recast into the upper bound on the graviton mass. Throughout this work, the light speed is defined as unity.

Upon a SGWB, the time of arrivals of radio pulses from two pulsars would be spatially correlated, with the angular correlation defined as

$$\gamma_{ab}(v_g) = \sum_\ell \frac{2\ell+1}{4\pi} C_\ell P_\ell(\cos\zeta_{ab}) \ , \tag{2}$$

where the subscript $_{ab}$ stands for the cross correlation of two pulsars a and b with the angular separation ζ_{ab}, and the angular power spectrum C_ℓ is defined as

$$C_\ell = \pi^{-1/2} J_\ell(v_g, fD_a) J^*_\ell(v_g, fD_b) \ , \tag{3}$$

where $f = \omega/(2\pi)$ is the frequency of gravitational waves, D_c denotes a distance to the c-th pulsar. To simplify the above definition, we have introduced a new function of the form

$$J_\ell(v_g, y) = \sqrt{2}\pi i^\ell \sqrt{\frac{(\ell+2)!}{(\ell-2)!}} \int_0^{2\pi y v_g} \frac{dx}{v_g} e^{ix/v_g} \frac{j_\ell(x)}{x^2} \ , \tag{4}$$

where $j_\ell(x)$ denotes the spherical Bessel function with ℓ-th multipole. Following Refs. [7, 15], we recast the angular correlation $\gamma_{ab}(v_g)$ into ORFs $\Gamma_{ab}(v_g)$ by normalizing the former such that $\Gamma_{aa}(v_g = 1) = 0.5$, where the subscript $_{aa}$ stands for the auto correlation of a-th pulsar. Note that the HD correlation curves are recovered by the above correlations in the massless limit.

In Fig. 1 and Fig. 2, we show the difference of ORFs between the massive gravitons and the massless gravitons. For comparison, we also reproduce the observed ORFs by NANOGrav [2] (see Fig. 1) and CPTA [3] (see Fig. 2). Roughly, it seems that the observed ORFs fit the massive gravitons better than the massless gravitons. The data analysis in the following section would be proved to support such suspicions.

III. DATA ANALYSIS AND RESULTS

For the NANOGrav 15-year data release, there are 67 pulsars with a timing baseline longer than 3 years monitored, implying 2,211 distinct pairs in total. Each pair has a deterministic angular separation. Based on those datasets, the authors of Ref. [2] constructed a minimally modeled Bayesian reconstruction of the inter-pulsar correlation pattern by employing spline

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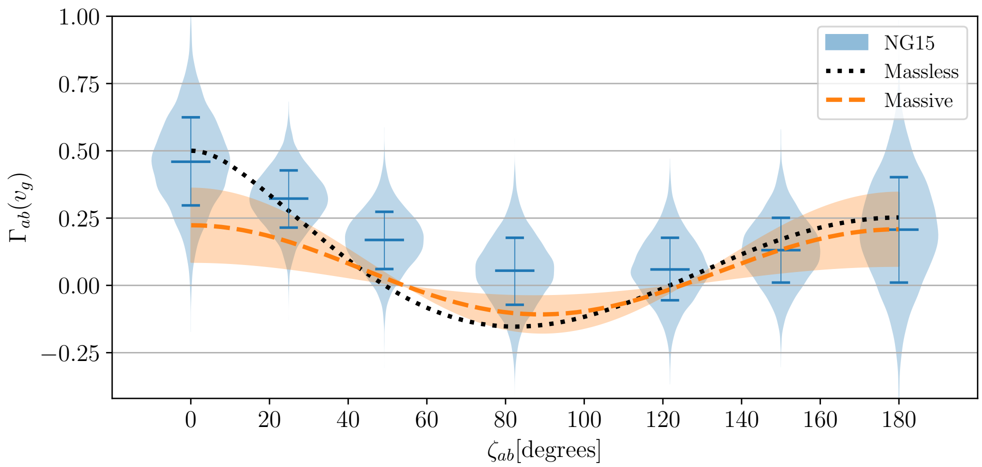

FIG. 1. Comparison between the ORFs of massive gravitons and those of massless gravitons. The orange shaded region stands for the cosmic variance. The NANOGrav 15-year data points are shown as shaded violins for comparison.

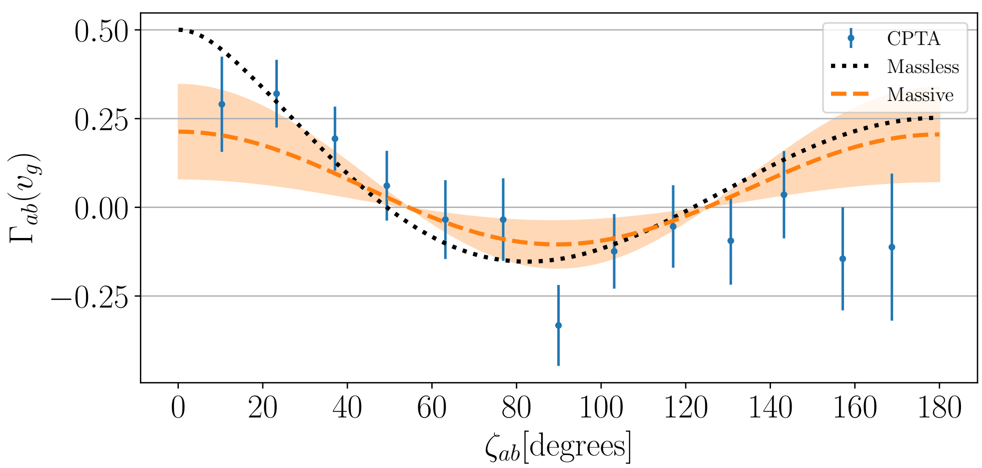

FIG. 2. Comparison between the ORFs of massive gravitons and those of massless gravitons. The orange shaded region stands for th cosmic variance. The CPTA first-release data points are shown for comparison.

interpolation over seven spline-knot positions, i.e., Fig. 1(d) of the paper. For the CPTA first data release [3], there are 57 millisecond pulsars monitored. The 4.6σ statistical significance of the HD correlation between those pulsars has been found around 14 nHz, see Fig. 4 of the data release paper.

Analyzing the above NANOGrav and CPTA datasets of the spatial correlations, we infer

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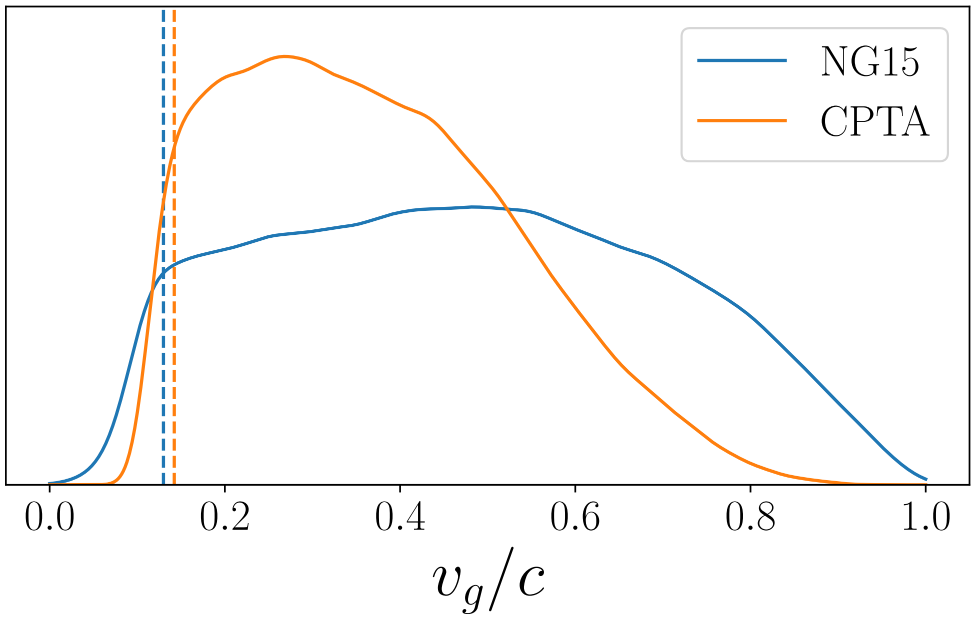

FIG. 3. Posteriors of the graviton speed v_g inferred from the NANOGrav 15-year data release and the CPTA first data release. The vertical dashed lines stand for the 95% confident lower limits.

the graviton speed, or equivalently, the graviton mass, by using the log-likelihood as follows

$$-2\ln\mathcal{L}(v_g|\mathrm{D}) = \sum_{\zeta_{ab}} \left(\frac{\Gamma_{ab}(v_g) - \Gamma_{ab}^{\mathrm{D}}}{\sigma_{ab}^{\mathrm{D}}}\right)^2 , \tag{5}$$

where Γ_{ab}^{D} stands for the observed ORFs for the binned angular separation ζ_{ab}, σ_{ab}^{D} stands for the corresponding 1σ uncertainty, D denotes the NANOGrav or CPTA datasets, and the summation runs over all the binned angular separations. Note that the above uncertainties also contain the cosmic variance [7, 15, 16].

For our data analysis, the parameter to be inferred is the graviton speed v_g. We let the corresponding priors to be uniform, i.e., $v_g \in [10^{-2}, 1]$, and conduct a Markov-Chain Monte-Carlo sampling by using the public code `cobaya` [17]. We also use the public `PTAfast` package [15] to compute ORFs. The resulting posteriors of v_g will be recast into the posteriors of m_g, following the relation in Eq. (1). Therefore, we will then obtain the upper limit on m_g at 95% confidence level.

Our results are shown as follows. The posteriors of v_g are depicted in Fig. 3. We label the 95% confident lower limits on v_g with vertical dashed lines. They are shown to be $v_g \gtrsim 0.13$ for NANOGrav and $v_g \gtrsim 0.14$ for CPTA. Compared with NANOGrav, CPTA favors a relatively smaller speed of gravitons. We further display the posteriors of m_g in Fig. 4. The

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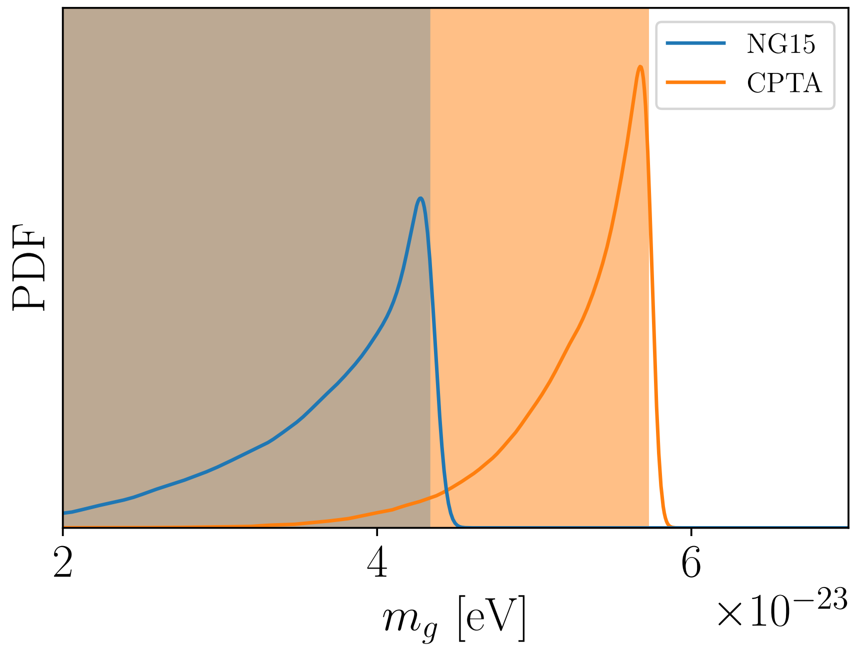

FIG. 4. Posteriors of the graviton mass inferred from the NANOGrav 15-year data release and the CPTA first data release. The shaded regions stand for the allowed parameter space at 95% confidence level.

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shaded regions stand for the allowed parameter space at 95% confidence level. Therefore, we find upper limits on m_g at 95% confidence level, namely, $m_g \lesssim 4.3 \times 10^{-23}$ eV for NANOGrav and $m_g \lesssim 5.7 \times 10^{-23}$ eV for CPTA. We find that the two bounds are consistent with each other. They stand for the state-of-the-art upper bounds on the graviton mass.

IV. CONCLUSION

In this work, we investigated the graviton mass bounds through analysis of the NANOGrav 15-year dataset and the CPTA first data release. Analyzing the data points of ORFs observed by the two observatories, we inferred the allowed parameter interval for the graviton speed, particularly, the posteriors. Recasting the posteriors of graviton speed into the posteriors of graviton mass, we obtained the state-of-the-art upper limits on the graviton mass, i.e., $m_g \lesssim \text{few} \times 10^{-23}$ eV at 95% confidence level.

There may be implications of our results for the ultralight tensor dark matter [18, 19], which may account for the mystery of dark matter in the universe. In particular, the

ultralight dark matter in the mass range $m_{\rm uldm} \sim 10^{-22}$eV was used for conquering several shortcomings of the traditional cold dark matter [20, 21]. The ultralight tensor dark matter behaves like the massive gravitons, indicating possible imprints of it on PTAs. Since our results were obtained through analysis of the recent PTA datasets, we find that the preferred mass range of ultralight tensor dark matter is compatible with the upper bounds on graviton mass of this current work. A similar work resulting from analysis of the NANOGrav 12.5-year dataset can be found in Ref. [22].

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